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THE USE OF STATISTICAL METHODS IN THE DETERMINATION OF THE PARAMETERS OF LINEAR MICROWAVE JUNCTIONS

by

S. W. Maley

UNIVERSITY OF COLORADO
Department of Electrical Engineering
Boulder, Colorado

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THE USE OF STATISTICAL METHODS IN THE DETERMINATION OF THE PARAMETERS OF LINEAR MICROWAVE JUNCTIONS

1.0 GENERAL ELECTRICAL NETWORKS

1.1 Introduction

A linear network transforms quantities such as impedance, admittance, and reflection coefficient by a linear fractional transformation. A commonly occurring problem is the determination of the parameters of this transformation from measurements on the network. A number of methods of determining the parameters have been discussed in the literature. [Beatty, Macphereson, 1953; Deschamps, 1953; Felson, Oliver, 1954; Mittra, King 1962]. Most of these methods are graphical and have limitations on the accuracy obtainable with them. The method described below makes use of statistical techniques to give values for the parameters which are the best, in the least squares sense, obtainable from the measured data. The use of a greater amount of measured data will reduce the probable error in the results. This is in contract to most other methods in which greater accuracy can be obtained only by increasing the precision of the individual measurements. A particular application of this technique to microwave junctions is discussed in Section 2.

1.2 Theory

Let the quantity X be transformed into the quantity Y by a network which may be described by the parameters A, B, and C. The transformation may be written

$$Y = \frac{A + BX}{-C + X} . \tag{1.1}$$

The problem is to determine the parameters A, B, and C from measured values of X and Y. The reason for the negative sign on the C will become apparent later. Let measured values of X be denoted by X_j, $j = 1, 2, \ldots$, and let the corresponding measured values of Y be Y_j, $j = 1, 2, \ldots$. If three measured sets of corresponding values of X and Y are known, they can be inserted into equation (1.1) to give 3 linear equations which may then be

solved for A, B, and C. To use a greater number of measurements and thereby obtain greater reliability of the result, the method of multiple linear regression [Hoel, 1954] may be used. Equation (1.1) may be written

$$A + BX + CY = XY. \tag{1.2}$$

Let the measured data consist of the n sets of values, X_i, Y_i, and X_iY_i where i = i, 2, 3, ..., n. n must be equal to or greater than 3 for a unique solution for A, B, and C to exist. The normal equations [Hoel, 1954] corresponding to equation (1.2) may be written:

$$\begin{aligned}
An + B\sum_{j=1}^{n} X_j + C\sum_{j=1}^{n} Y_j &= \sum_{j=1}^{n} X_jY_j, \\
A\sum_{j=1}^{n} X_j + B\sum_{j=1}^{n} (X_j)^2 + C\sum_{j=1}^{n} Y_jX_j &= \sum_{j=1}^{n} (X_j)^2 Y_j, \\
A\sum_{j=1}^{n} Y_j + B\sum_{j=1}^{n} X_jY_j + C\sum_{j=1}^{n} (Y_j)^2 &= \sum_{j=1}^{n} X_j(Y_j)^2 .
\end{aligned} \tag{1.3}$$

These equations can be solved for the 3 unknowns, A, B, and C. The use of the negative sign in equation (1.1) makes the coefficient matrix in (1.3) symmetric; this sometimes simplifies the solution of the equations. This method of determining A, B, and C is the best in the sense of minimizing the sum of the squares of the differences between the measured values of XY and the values of XY as found from equation (1.2) in terms of the corresponding measured values of X and Y, or in symbols, the minimizing of the quantity

$$\sum_{j=1}^{n} (X_jY_j - A - BX_j - CY_j)^2 .$$

A modification of the above procedure sometimes shortens the calculations. Make the following changes of variables in equation (1.2):

$$x = X - \bar{X} ,$$

$$y = Y - \bar{Y} ,$$

$$xy = XY - (\overline{XY}) , \tag{1.4}$$

where

$$\bar{X} = \frac{1}{n} \sum_{j=1}^{n} X_j ,$$

$$\bar{Y} = \frac{1}{n} \sum_{j=1}^{n} Y_j , \tag{1.5}$$

$$(\overline{XY}) = \frac{1}{n} \sum_{j=1}^{n} X_j Y_j .$$

Then equation (1.2) becomes

$$a + Bx + Cy = xy , \tag{1.6}$$

where

$$a = A + B\bar{X} + C\bar{Y} - (\overline{XY}). \tag{1.7}$$

The quantities x_j, y_j, and $(xy)_j$ will be defined as follows:

$$x_j = X_j - \bar{X} ,$$

$$y_j = Y_j - \bar{Y} , \tag{1.8}$$

$$(xy)_j = X_j Y_j - (\overline{XY}) .$$

Now the normal equations corresponding to equation (1.6) are

$$an + B \sum_{j=1}^{n} x_j + C \sum_{j=1}^{n} y_j = \sum_{j=1}^{n} (xy)_j \, ,$$

$$a \sum_{j=1}^{n} x_j + B \sum_{j=1}^{n} x_j^2 + C \sum_{j=1}^{n} x_j y_j = \sum_{j=1}^{n} (xy)_j \, x_j \, , \tag{1.9}$$

$$a \sum_{j=1}^{n} y_j + B \sum_{j=1}^{n} x_j y_j + C \sum_{j=1}^{n} y_j^2 = \sum_{j=1}^{n} (xy)_j \, Y_j \, .$$

It is apparent from equations (1.4) and (1.5) that

$$\sum_{j=1}^{n} x_j = \sum_{j=1}^{n} y_j = \sum_{j=1}^{n} (xy)_j = 0 \, . \tag{1.10}$$

Therefore the first of equations (1.9) reduces to

$$a = 0 \, . \tag{1.11}$$

The second and third of equations (1.9) may now be solved for B and C.

$$B = \frac{\sum_{j=1}^{n} (xy)_j \, x_j \sum_{j=1}^{n} y_j^2 - \sum_{j=1}^{n} x_j y_j \sum_{j=1}^{n} (xy)_j \, y_j}{\sum_{j=1}^{n} x_j^2 \sum_{j=1}^{n} y_j^2 - \left[\sum_{j=1}^{n} x_j \, y_j \right]^2} \, .$$

$$C = \frac{\sum_{j=1}^{n} x_j^2 \sum_{j=1}^{n} (xy)_j \, y_j - \sum_{j=1}^{n} x_j y_j \sum_{j=1}^{n} (xy)_j \, x_j}{\sum_{j=1}^{n} x_j^2 \sum_{j=1}^{n} y_j^2 - \left[\sum_{j=1}^{n} x_y \, y_j \right]^2} \, . \tag{1.12}$$

Finally A may be obtained from equations (1.7) and (1.11).

$$A = \overline{XY} - B\overline{X} - C\overline{Y} \,. \tag{1.13}$$

In general the variables X and Y as well as the parameters A, B, and C in equation (1.1) will be complex. It is usually more convenient to work in terms of the real and imaginary parts of complex quantities. Let the real part of a quantity, say x, be denoted by a single prime and the imaginary part by a double prime; thus $x = x' + ix''$ where $i = \sqrt{-1}$. Using this notation, definitions (1.4) and (1.5) become

$$\begin{aligned} x' &= X' - \overline{X}' \,, & x'' &= X'' - \overline{X}'' \,, \\ y' &= Y' - \overline{Y}' \,, & y'' &= Y'' - \overline{Y}'' \,, \\ (xy)' &= X'Y' - X''Y'' - (\overline{XY})' \,, & (xy)'' &= X'Y'' + X''Y' - (\overline{XY})'' \end{aligned} \tag{1.14}$$

where

$$\begin{aligned} \overline{X}' &= \frac{1}{n}\sum_{j=1}^{n} X_j' \,, & \overline{X}'' &= \frac{1}{n}\sum_{j=1}^{n} X_j'' \,, \\ \overline{Y}' &= \frac{1}{n}\sum_{j=1}^{n} Y_j' \,, & \overline{Y}'' &= \frac{1}{n}\sum_{j=1}^{n} Y_j'' \,, \\ (\overline{XY})' &= \frac{1}{n}\sum_{j=1}^{n} X_j'Y_j' - \frac{1}{n}\sum_{j=1}^{n} X_j''\,Y_j'' \,, & (\overline{XY})'' &= \frac{1}{n}\sum_{j=1}^{n} X_j'Y_j'' + \frac{1}{n}\sum_{j=1}^{n} X_j''\,Y_j' \,. \end{aligned} \tag{1.15}$$

Equations (1.8) become

$$\begin{aligned} x_j' &= X_j' - \overline{X}' \,, & x_j'' &= X_j'' - \overline{X}'' \,, \\ y_j' &= Y_j' - \overline{Y}' \,, & y_j'' &= Y_j'' - \overline{Y}'' \,, \\ (xy)'_j &= X_j'Y_j' - X_j''\,Y_j'' - (\overline{XY})' \,, & (xy)''_j &= X_j'\,Y_j'' + X_j''\,Y_j' - (\overline{XY})'' \,. \end{aligned} \tag{1.16}$$

The definitions given in (1.14), (1.15), and (1.16) may now be substituted into (1.12) and (1.13) to give complex expressions for A, B, and C.

$$B = \left\{ \sum_{j=1}^{n} \left[(xy)_j' + i(xy)_j''\right] (x_j' + ix_j'') \sum_{j=1}^{n} (y_j' + iy_j'')^2 \right.$$

$$\left. - \sum_{j=1}^{n} (x_j' + ix_j'')(y_j' + iy_j'') \sum_{j=1}^{n} \left[(xy)_j' + i(xy)_j''\right] (y_j' + iy_j'') \right\}$$

$$\div \left\{ \sum_{j=1}^{n} (x_j' + ix_j'')^2 \sum_{j=1}^{n} (y_j' + iy_j'')^2 \right.$$

$$\left. - \left[\sum_{j=1}^{n} (x_j' + ix_j'')(y_j' + iy_j'') \right]^2 \right\}$$

$$(1.17)$$

$$C = \left\{ \sum_{j=1}^{n} (x_j' + ix_j'')^2 \sum_{j=1}^{n} \left[(xy)_j' + i(xy)_j''\right] (y_j' + iy_j'') \right.$$

$$\left. - \sum_{j=1}^{n} (x_j' + ix_j'')(y_j' + iy_j'') \sum_{j=1}^{n} \left[(xy)_j' + i(xy)_j''\right] (x_j' + ix_j'') \right\}$$

$$\div \left\{ \sum_{j=1}^{n} (x_j' + ix_j'')^2 \sum_{j=1}^{n} (y_j' + iy_j'')^2 \right.$$

$$\left. - \left[\sum_{j=1}^{n} (x_j' + ix_j'')(y_j' + iy_j'') \right]^2 \right\}$$

$$A = (\overline{XY})' + i(\overline{XY})'' - B(\overline{X}' + i\overline{X}'') - C(\overline{Y}' + i\overline{Y}'')$$

The real and imaginary parts of B and C may be obtained by rationalizing the above expressions; however the results may be presented in a more concise form by going back to the last two of equations (1.9). Taking (1.11) into consideration and separating these equations into real and imaginary parts results in the following system of equations:

$$\begin{aligned} B'd - B''e + C'f - C''g &= h , \\ B'e + B''d + C'g + C''f &= k , \\ B'f - B''g + C'\ell - C''m &= p , \\ B'g + B''f + C'm + C''\ell &= q , \end{aligned} \qquad (1.18)$$

where

$$
\begin{aligned}
d &= \sum_{j=1}^{n} (x_j')^2 - \sum_{j=1}^{n} (x_j'')^2 , \\
e &= 2 \sum_{j=1}^{n} x_j' \, x_j'' , \\
f &= \sum_{j=1}^{n} x_j' \, y_j' - \sum_{j=1}^{n} x_j'' \, y_j'' , \\
g &= \sum_{j=1}^{n} x_j' \, y_j'' + \sum_{j=1}^{n} x_j'' \, y_j' , \\
h &= \sum_{j=1}^{n} (xy)_j' \, x_j' - \sum_{j=1}^{n} (xy)_j'' \, x_j'' , \\
k &= \sum_{j=1}^{n} (xy)_j' \, x_j'' + \sum_{j=1}^{n} (xy)_j'' \, x_j' , \\
\ell &= \sum_{j=1}^{n} (y_j')^2 - \sum_{j=1}^{n} (y_j'')^2 , \\
m &= 2 \sum_{j=1}^{n} y_j' \, y_j'' , \\
p &= \sum_{j=1}^{n} (xy)_j' \, y_j' - \sum_{j=1}^{n} (xy)_j'' \, y_j'' , \\
q &= \sum_{j=1}^{n} (xy)_j' \, y_j'' + \sum_{j=1}^{n} (xy)_j'' \, y_j' .
\end{aligned}
\tag{1.19}
$$

The solutions for B', B", C', and C" may now be written in terms of determinants.

$$B' = \frac{1}{D}\begin{vmatrix} h & -e & f & -g \\ k & d & g & f \\ p & -g & \ell & -m \\ q & f & m & \ell \end{vmatrix};$$

$$B' = \frac{1}{D}\begin{vmatrix} d & h & f & -g \\ e & k & g & f \\ f & p & \ell & -m \\ g & q & m & \ell \end{vmatrix};$$

$$C' = \frac{1}{D}\begin{vmatrix} d & -e & h & -g \\ e & d & k & f \\ f & -g & p & -m \\ g & f & q & \ell \end{vmatrix};$$

$$C'' = \frac{1}{D}\begin{vmatrix} d & -e & f & h \\ e & d & g & k \\ f & -g & \ell & p \\ g & f & m & q \end{vmatrix};$$

where

$$D = \begin{vmatrix} d & -e & f & -g \\ e & d & g & f \\ f & -g & \ell & -m \\ g & f & m & \ell \end{vmatrix}.$$

The formulas given above may be used to determine the parameters A, B, and C of the linear fractional transformation (1.1). The parameters are given in terms of sets of measured values of X and Y, and the method makes provision for the use of 3 or more such sets. The use of a larger number of sets of measured values of X and Y will reduce the probable error in the resulting values for A, B, and C. Therefore the use of this method makes it possible to substitute a greater number of measurements for greater precision of measurements.

Any linear four-terminal network can be completely characterized by the parameters of the linear fractional transformation with which it transforms a quantity such as impedance, admittance, or reflection coefficient. If it is necessary to find other sets of parameters for the network, these can be obtained from the A, B, and C.

2.0 TWO-PORT MICROWAVE JUNCTIONS

2.1 Theory

Let the two-port microwave junction be as represented in Fig. 1.

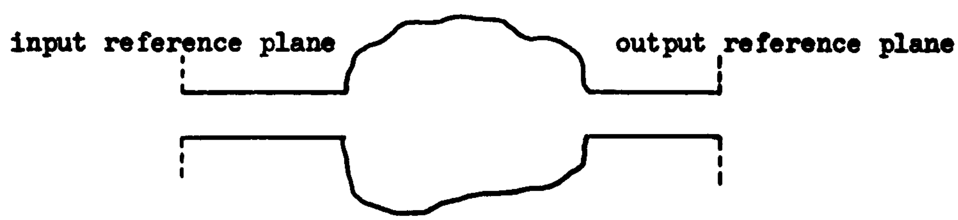

Fig. 1, Two-port microwave junction

Let the reflection coefficient of the load be Γ_r at the output reference plane, and let the reflection coefficient of the junction together with the load be Γ_g at the input reference plane. Γ_g is related to Γ_r by a linear fractional transformation such as

$$\Gamma_g = \frac{A + B\,\Gamma_r}{-C + \Gamma_r} \,. \tag{2.1}$$

The parameters A, B, and C describe the two-port junction. A, B, and C may be evaluated in terms of a number of experimental measurements of Γ_g and Γ_r. Let the real and imaginary parts of all complex expressions be denoted by single and double primes respectively. Thus, for example, $\Gamma_g = \Gamma_g' + i\,\Gamma_g''$ where $i = (-1)^{1/2}$. Let n be the number of sets of measurements of Γ_g and Γ_r. The sets of corresponding measured quantities will be denoted by Γ_{gj} and Γ_{rj} where j takes the values 1

through n. In terms of the real and imaginary components we have
$\Gamma_{gj} = \Gamma'_{gj} + i\,\Gamma''_{gj}$ and $\Gamma_{rj} = \Gamma'_{rj} + i\,\Gamma''_{rj}$.

We now define the following quantities:

$$\overline{\Gamma}'_g = \frac{1}{n} \sum_{j=1}^{n} \Gamma'_{gj} , \qquad \overline{\Gamma}''_g = \frac{1}{n} \sum_{j=1}^{n} \Gamma''_{gj} ,$$

$$\overline{\Gamma}'_r = \frac{1}{n} \sum_{j=1}^{n} \Gamma'_{rj} , \qquad \overline{\Gamma}''_r = \frac{1}{n} \sum_{j=1}^{n} \Gamma''_{rj} ,$$

$$\overline{(\Gamma_g \Gamma_r)'} = \frac{1}{n} \sum_{j=1}^{n} \Gamma'_{gj}\, \Gamma'_{rj} - \frac{1}{n} \sum_{j=1}^{n} \Gamma''_{gj}\, \Gamma''_{rj}, \quad \overline{(\Gamma_g \Gamma_r)''} = \frac{1}{n} \sum_{j=1}^{n} \Gamma'_{gj}\, \Gamma''_{rj}$$

$$+ \frac{1}{n} \sum_{j=1}^{n} \Gamma''_{gj}\, \Gamma'_{rj} , \tag{2.2}$$

$$\gamma'_{gj} = \Gamma'_{gj} - \overline{\Gamma}'_g , \qquad \gamma'_{gj} = \Gamma''_{gj} - \overline{\Gamma}''_g ,$$

$$\gamma'_{rj} = \Gamma'_{rj} - \overline{\Gamma}'_r , \qquad \gamma''_{rj} = \Gamma''_{rj} - \overline{\Gamma}''_{rj} ,$$

$$(\gamma_g \gamma_r)'_j = \Gamma'_{gj}\, \Gamma'_{rj} - \Gamma''_{gj}\, \Gamma''_{rj} - \overline{(\Gamma_g \Gamma_r)'}, \quad (\gamma_g \gamma_r)'' = \Gamma'_{gj}\, \Gamma''_{rj}$$

$$+ \Gamma''_{gj}\, \Gamma'_{rj} - \overline{(\Gamma_g \Gamma_r)''} .$$

The parameters A, B, and C may now be found from (1.17)

$$B = \left\{ \sum_{j=1}^{n} [(\gamma_g \gamma_r)'_j + i(\gamma_g \gamma_r)''_j](\gamma'_{gj} + i\gamma''_{gj}) \sum_{j=1}^{n} (\gamma'_{rj} + i\gamma''_{rj})^2 \right.$$

$$- \sum_{j=1}^{n} (x'_{gj} + i\gamma''_{gj})(\gamma'_{rj} + i\gamma''_{rj}) \sum_{j=1}^{n} [(\gamma_g \gamma_r)'_j + i(\gamma_g \gamma_r)''_j]$$

$$\left. (\gamma'_{rj} + i\gamma''_{rj}) \right\} \div \left\{ \sum_{j=1}^{n} (\gamma'_{gj} + i\gamma''_{gj})^2 \sum_{j=1}^{n} (\gamma'_{rj} + \gamma''_{rj})^2 \right.$$

$$\left. - \left[\sum_{j=1}^{n} (\gamma'_{gj} + i\gamma''_{gj})(\gamma'_{rj} + i\gamma''_{rj}) \right]^2 \right\},$$

$$C = \left\{ \sum_{j=1}^{n} (\gamma'_{gj} + i\gamma''_{gj})^2 \sum_{j=1}^{n} [(\gamma_g \gamma_r)'_j + i(\gamma_g \gamma_r)''_j](\gamma'_{rj} + i\gamma''_{rj}) \right. \tag{2.3}$$

$$- \sum_{j=1}^{n} (\gamma'_{gj} + i\gamma''_{gj})(\gamma'_{rj} + i\gamma''_{rj}) \sum_{j=1}^{n} [(\gamma_g \gamma_r)'_j + i(\gamma_g \gamma_r)''_j]$$

$$\left. (\gamma'_{gj} + i\gamma''_{gj}) \right\} \div \left\{ \sum_{j=1}^{n} (\gamma'_{gj} + i\gamma''_{gj})^2 \sum_{j=1}^{n} (\gamma'_{rj} + i\gamma''_{rj})^2 \right.$$

$$\left. - \left[\sum_{j=1}^{n} (\gamma'_{gj} + i\gamma''_{gj})(\gamma'_{rj} + i\gamma''_{rj}) \right]^2 \right\},$$

$$A = \overline{\Gamma_g \Gamma_r}' + i\, \overline{\Gamma_g \Gamma_r}'' - B(\bar{\Gamma}'_g + i\bar{\Gamma}''_g) - C(\bar{\Gamma}'_r + i\bar{\Gamma}''_r) .$$

Alternatively the real and imaginary parts of B and C, denoted by single and double primes respectively, can be found by solving the following set of equations:

$$
\begin{aligned}
B'd - B''e + C'f - C''g &= h \,, \\
B'e + B''d + C'g + C''f &= k \,, \\
B'f - B''g + C'\ell - C''m &= p \,, \\
B'g + B''f + C'm + C''\ell &= q \,,
\end{aligned}
\tag{2.4}
$$

where

$$d = \sum_{j=1}^{n} (\gamma'_{gj})^2 - \sum_{j=1}^{n} (\gamma''_{gj})^2 \,, \qquad e = 2\sum_{j=1}^{n} \gamma'_{gj}\, \gamma''_{gj} \,,$$

$$f = \sum_{j=1}^{n} \gamma'_{gj}\, \gamma'_{rj} - \sum_{j=1}^{n} \gamma''_{gj}\, \gamma''_{rj} \,, \qquad g = \sum_{j=1}^{n} \gamma'_{gj}\, \gamma'_{rj} + \sum_{j=1}^{n} \gamma''_{gj}\, \gamma'_{rj} \,,$$

$$h = \sum_{j=1}^{n} (\gamma_g \gamma_r)'_j\, \gamma'_{gj} - \sum_{j=1}^{n} (\gamma_g \gamma_r)''_j\, \gamma''_{gj} \,, \quad k = \sum_{j=1}^{n} (\gamma_g \gamma_r)'_j\, \gamma''_{gj} + \sum_{j=1}^{n} (\gamma_g \gamma_r)''_j\, \gamma'_{gj} \,,$$

$$\ell = \sum_{j=1}^{n} (\gamma'_{rj})^2 - \sum_{j=1}^{n} (\gamma''_{rj})^2 \,, \qquad m = 2\sum_{j=1}^{n} \gamma'_{rj}\, \gamma''_{rj} \,,$$

$$p = \sum_{j=1}^{n} (\gamma_g \gamma_r)'_j\, \gamma'_{rj} - \sum_{j=1}^{n} (\gamma_g \gamma_r)''_j\, \gamma''_{rj} \,, \quad q = \sum_{j=1}^{n} (\gamma_g \gamma_r)'_j\, \gamma''_{rj} + \sum_{j=1}^{n} (\gamma_g \gamma_r)''_j\, \gamma'_{rj} \,.$$

The solution to equations (2.4) gives values for $B = B' + iB''$ and $C = C' + iC''$. Then A may be found from the last of equations (2.3).

2.2 Conclusions

The network parameters A, B, and C which characterize a two part microwave network by means of equation (2.1) have been determined as functions of a set of corresponding measurements of input and output reflection coefficients. It can be expected, as a result of the statistical averaging inherent in this method, that an increase in the number of measurements used will result in smaller probable errors in the results. This method has been used with good results to determine the parameters of a feed system for an X-band antenna. In this particular application the antenna on the output of the network was replaced by a moveable short circuit so that the output reflection coefficient could be found in terms of the distance between the output reference plane and the short circuit. The input reflection coefficient was then measured for a series of values of the output reflection coefficient. This measured data was then used to find the parameters A, B, and C.

This analysis describes a method for determining the parameters in equation (2.1) which relates the input and output reflection coefficients of a two part microwave network. It is apparent, however, that the method can be used to determine the parameters of the transformation for any quantity which the network transforms by means of a linear fractional transformation. For example a two port microwave network transforms impedance by means of the same type of transformation as equation (2.1); therefore the parameters of the impedance transformation could be found from the equations given in this paper simply by substituting the input and output impedance measurements for the input, and output reflection coefficient measurements.

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